

Using brain-based measures to compose teams: How individual capabilities and team collaboration strategies jointly shape performance

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Advances in understanding neural processes open the possibility of using brain-based measures to compose collaborative work teams. Neuroimaging studies have shown that individual differences in patterns of brain activity can predict differences in performance of specific tasks. We extended this finding by examining performance not simply by a single brain, but by pairs of brains. We used measures derived from brain-based studies to compose 100 two-person teams in which members' roles were either congruent or incongruent with their individual abilities. The assessed abilities are rooted in the visual system, which comprises independent "spatial" and "object" subsystems. The team task required one member to navigate through a virtual maze (a spatial task) and the other to remember "tag" repetitions of complex "greebles" (an object-properties task). Teams in which members' role assignments were congruent with their abilities performed better than incongruent teams and teams in which both members scored high on only one of the abilities. In addition, verbal collaboration enabled members of incongruent teams to overcome their compositional disadvantage but did not enhance the performance of congruent teams—and actually impaired performance in teams in which both members were adept in only one of the two necessary abilities. The findings show that knowledge about brain systems can not only be used to compose teams, but also provides insights into how teams can best perform.

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Cognitive neuroscience has made great progress in characterizing specific neural systems, such as those underlying various aspects of memory and perception. Moreover, researchers in cognitive neuroscience have pushed beyond nomothetic studies, which characterize “average” or modal brain systems, to document that individuals differ markedly in how well specific brain systems function—and that such differences in brain function predict differences in performance (e.g., prefrontal cortex is more important during memory retrieval—as indicated by the amount of activation—for slower participants than for faster participants; Rypma & D’Esposito, 1999; see also Rypma, Berger & D’Esposito, 2002). Furthermore, individual differences in performance arise, in part, from the efficacy of interactions among different parts of the brain; prefrontal executive functions appear to be more important in people who perform relatively slowly (Rypma et al., 2006). Similarly, Kosslyn and colleagues (Kosslyn, Thompson, Kim, Rauch, & Alpert, 1996) found that individual differences in activation of several brain areas working together predicted response times in a simple mental imagery task, and Kosslyn et al. (2004) found that the relative amount of activation in different brain areas predicted performance in different mental imagery tasks.

The present article extends such findings to the level of the interacting group. We were guided by a very simple and rough analogy: We regarded a group of people as an emergent entity, akin to a brain. In this case, each individual in a group can play the role of a distinct brain system, with the different systems working together. If we look at teams this way, an effective team would include individuals who, in effect, function as the brain systems that are needed to accomplish the group task. This simple analogy led us to push the notion developed by Rypma et al. (2006), which focuses on co-ordination of brain systems within a single head, to apply to co-ordination of brain systems *between* individual heads. Our approach uses neuroscience to inspire investigation of the nature of social interactions.

We focus here on individual differences in the functioning of two brain systems that are clearly specialized for different aspects of processing and that are localized in different parts of the brain. Specifically, the difference between the ventral visual system (which extends from the occipital lobes to the inferior temporal lobes) and the dorsal visual system (which extends from the occipital lobes to the posterior parietal lobes) is

extraordinarily well supported by converging evidence from multiple laboratories using diverse methodologies (e.g., animal lesion studies by Ungerleider & Mishkin, 1982; human neuroimaging studies by Courtney, Ungerleider, Keil, & Haxby, 1996; human behavioral studies using a dual-task paradigm by Mohr & Linden, 2005). The ventral visual system plays a central role in processing shapes and other properties of objects such as color and texture, whereas the dorsal visual system plays a central role in processing spatial relations (Cabeza & Nyberg, 2000; Kosslyn, 1994; Ungerleider & Haxby, 1994). Of particular relevance for our purposes is the finding from an individual-differences study that tests of object processing and tests of spatial processing load on two distinct factors, indicating that they measure different underlying abilities, and that individuals can have high object-processing ability without having high spatial-processing ability, and vice-versa (Chen, Myerson, Hale, & Simon, 2000). Indeed, most analyses have shown that the correlation between spatial and object imagery ability is—if anything—slightly negative (Blajenkova, Kozhevnikov, & Motes, 2006), suggesting that individuals who are strong object visualizers tend not to be strong spatial visualizers and vice versa.

Rather than further document the functional difference between these brain systems, we treated this distinction as an individual-differences dimension. Moreover, we drew upon newly created paper and pencil measures of the two types of processing to assess those individual differences. Specifically, we administered these measures online to a large sample and selected individuals who were selectively strong in either object or spatial visualization (see Kozhevnikov, Kosslyn, & Shephard, 2005, for a review). We then invited those individuals to come to our laboratory and work with a partner on a navigation task. Thus, the present work is not simply a novel approach to extending what has been learned about individual differences in brain function. Instead, it proposes a novel approach to composing teams. Researchers have grappled for decades with the question of how teams should be composed (e.g., Altman & Haythorn, 1967; Cattell, 1948), but remarkably few robust generalizations have emerged. Unlike previous efforts, the brain-based approach leads us to focus on the complementarity of team members’ task-specific abilities, rather than on a team’s overall level or variation on a particular trait.

Many previous studies of team composition have focused on the relationship between general mental ability and team performance; these studies typically demonstrated a positive relationship between the *mean* abilities of members and team performance (Barrick, Neubert, Mount, & Steward, 1998; LePine, 2005; Tziner & Eden, 1985). Other research on team composition examined the personality composition of teams; these studies typically focused on the sum or mean level of the personality attribute of interest, the variance among members, the proportion of members exhibiting a particular characteristic, or the scores of the highest- and lowest-standing members (Barrick et al., 1998; Demko, 2001; Neuman, Wagner, & Christiansen, 1999). The most consistent findings with respect to team personality composition are a curvilinear relationship between the level of most traits and performance (Demko, 2001) and a positive association between performance and the within-team variability of traits such as extraversion and emotional stability (Neuman et al., 1999). In contrast, in the brain-based approach to composing teams used in the present study, we predicted that *complementarity* of task-specific cognitive abilities would be more important than either the mean level or the variance of abilities. While prior work on teams in organizations has examined the performance effects of the diversity of knowledge and expertise of team members (e.g., Cummings, 2004; Jehn, Northcraft, & Neale, 1999; Stasser & Titus, 1985) traditional diversity research has not been operationalized as complementarity (e.g., where only one person holds each skill or piece of information) and the skills examined have not been strictly task-specific. Here, we focus on the complementarity of task-specific cognitive abilities. Specifically, we predicted that a team task that requires both spatial and object visualization would be better performed by a spatial visualizer working with an object visualizer. Returning to our guiding analogy, it is as if the different members of the group each can supply a key neural system, which then can work together in the team itself.

In addition, we analyzed the *joint* effects of team composition and performance strategy. It is not enough to have a team with the appropriate abilities. To be effective, the team must also devise a performance strategy that allows it to use its members' talents well (Hackman, 2002; Hackman, Brousseau, & Weiss, 1976; Salas & Fiore, 2004). When members' abilities are

complementary, the group must ensure that each member's role on the task is appropriately matched to his or her capabilities (Faraj & Sproull, 2000).

These considerations led us to predict that teams in which all of the necessary skills for a task are present *and* members' skills are well-matched to their role assignments will perform better than: (1) teams in which some skills are not present; and (2) teams in which skills are not congruent with role assignments. In addition, communication among team members should: (1) enhance team performance when abilities are present but *not* well-matched to roles; (2) *not* help teams when the members' abilities *are* well-matched to roles; and (3) *not* help teams when necessary skills are not present. In this way, parts of different people's brains may come to function together, leading to an emergent "group brain" in which the combined neural resources are greater than the simple sum of the parts. In fact, if such results are obtained, one might begin to argue that the brain evolved so that individuals can complement one another, allowing groups to have more cognitive capacity than is found in any single individual (cf. Wegner, 1987).

METHOD

To test these predictions, we conducted a study in which members of two-person teams had either "complementary" abilities (i.e., one member was high on one task-relevant ability and the second member was high on the other) or "homogeneous" abilities (i.e., both members were high on the same ability). When members had complementary abilities, they were assigned to task roles that were either congruent or incongruent with their abilities. This procedure yielded three conditions, which we refer to as "congruent," "incongruent," and "homogeneous."

Participants

The sample consisted of 100 teams composed of two partners. Sixty teams were complementary, of which 30 were "congruent" teams (the object visualizer and the spatial visualizer were assigned to appropriate roles) and 30 were "incongruent" (members were assigned to roles incongruent with their measured abilities). Forty teams were homogeneous, 20 in which both partners were

spatial visualizers, and 20 in which both partners were object visualizers.

Individuals were selected for participation based on their scores on two self-report measures: (1) the Visualizer-Verbalizer Cognitive Style Questionnaire (VVCSQ), an adaptation of the Mathematical Processing Instrument (see Kozhevnikov, Hegarty, & Mayer, 2002; Lean & Clements, 1981); and (2) the Object-Spatial Imagery Questionnaire (OSIQ; Blajenkova et al., 2006). The VVCSQ classifies an individual as a "verbalizer" or a "visualizer" based on the respondent's tendency to use verbal or visual strategies in solving a series of math problems. The OSIQ yields subscores for "spatial visualization" and "object visualization" cognitive styles that have been shown to correlate with spatial and object processing abilities (Blajenkova et al., 2006; Chabris et al., 2006; Kozhevnikov et al., 2005).¹

We began by screening a total of 2494 individuals online, using the web survey client SurveyMonkey (<http://www.surveymonkey.com>). Recruitment for this prescreening was conducted using online bulletin boards, and targeted the local community as well as specific interest groups that we expected to yield high concentrations of object or spatial visualizers. We considered respondents eligible for participation if the difference score between OSIQ object and spatial subscores was greater than 4 points (out of subscore scales of 15–75) and if the Visualizer-Verbalizer Cognitive Style Questionnaire score was greater than 7 points (out of 20, with low scores indicating verbalizer styles). In complementary teams, participants were paired with partners such that each partner's higher score (i.e., object or spatial) was greater than the other's score on the same scale. Of the respondents, 262 were classified as verbalizers and excluded from the pool, 1255 met our requirements for strong object visualization, and 385 met requirements for strong spatial visualization (592 were unclassified). Participants were aware that their results on the screening tests would influence whether they were invited to participate in the laboratory study, but they were not given feedback on how they scored. Among those who participated in the laboratory portion of the study, 77% described themselves as White or Caucasian, 65%

were female, and participant ages ranged from 18–60 with a median age of 24.

Materials and task

The experimental task was a computer-based maze consisting of a long, winding corridor with many hallways branching off, populated by complex, unfamiliar objects called "greebles" (Gauthier & Tarr, 1997; see Figure 1). Teams viewed the virtual maze environment on the monitor of a single 1 GHz eMac computer, with the keyboard situated in front and to the left of the display and a joystick situated in front and to the right. Design of the mazes, rendering and presentation of the images, and collection of teams' responses were implemented using the Psychophysics Toolbox extensions in Matlab (Brainard, 1997; Pelli, 1997). The teams' real-time view was rendered as a first-person perspective image of the three-dimensional space.

The greeble objects were chosen for their novelty and complexity to avoid any advantage of object familiarity while maximizing the difficulty of the task. Some of the greebles had an identical twin elsewhere in the maze, whereas others did not. We instructed the teams to navigate through the entire maze and to find and "tag" as many of the identical greeble pairs as possible, using the joystick to navigate and the keyboard to place and remove tags on the greebles. Teams earned a monetary reward based on their performance in navigating the maze and correctly tagging the greebles.

Procedure

Individuals were recruited to participate in the study by first being invited to complete our online pre-screening procedure, as described above. Those whose scores met the specified criteria were then invited to come to the lab and work with another participant on the experimental task. We assigned the team's condition and the members' roles prior to their arrival at the laboratory.

When participants arrived at the laboratory, we introduced them and explained to each member what his or her role would be in the task: one used the joystick to control navigation, and the other used the keyboard to tag and untag objects. In half of the complementary teams, participants

¹ Our version of this questionnaire also included 15 items under development for a subscore measuring the "verbalization" cognitive style, but we did not use these items in classifying or selecting subjects.

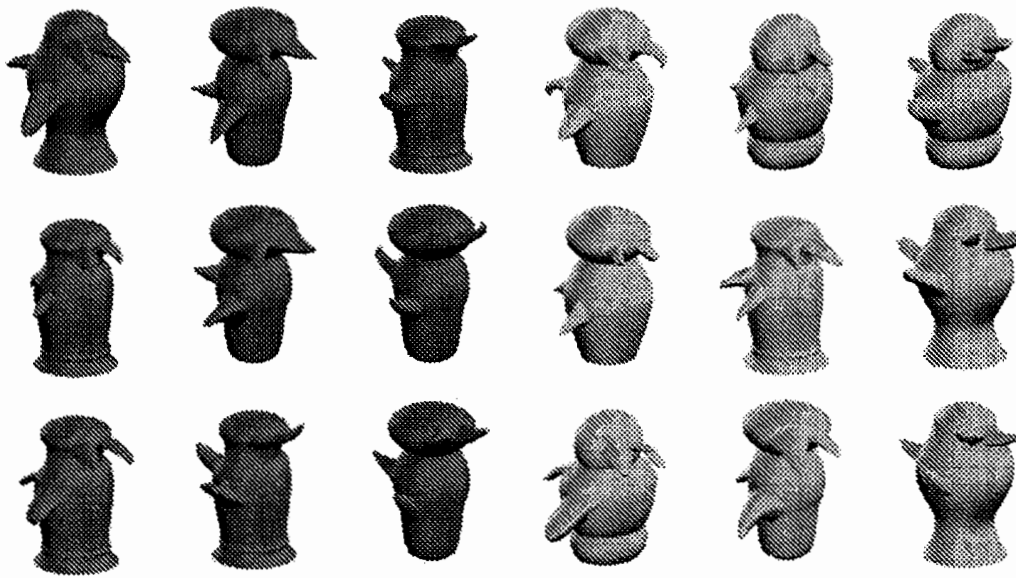


Figure 1. Images of objects, called “greebles,” that populated Maze 1 (purple) and Maze 2 (green). Images provided courtesy of Michael J. Tarr (Brown University, Providence, RI).

were assigned roles congruent with their cognitive abilities: the spatial visualizer controlled the joystick, and the object visualizer controlled the keyboard. In the other half of the complementary teams, participants were assigned incongruent roles, and in the homogenous teams, participants were assigned to roles randomly. Neither the team nor the investigator was aware of the participants' measured abilities. All teams were videotaped with the knowledge and consent of the participants.

Once the participants were introduced and seated in their assigned positions, they viewed an automated instruction sequence composed of text and animated graphics that described the task, including detailed explanations of the tagging procedure and the rules used for administering rewards, penalties, and bonuses. After verbally confirming that they had understood the instructions, team members were asked to cease all verbal and nonverbal communication; they were allowed to talk after completing Maze 1. The teams then navigated through two small practice mazes, each containing one greeble pair and four lone distractor greebles, receiving coaching from the investigator as necessary to ensure that they understood the task and the controls. During this practice period only, teams received feedback when they correctly tagged the greeble pair in each maze.

Following the practice period, teams navigated four mazes in sequence. Only findings from Mazes 1 and 2 are reported here because preliminary analyses of data from the Mazes 3 and 4 revealed flaws in their design, which made them so difficult that findings from them were not readily interpretable.² Mazes 1 and 2 contained 12 greebles each, including three pairs of identical greebles and six lone distractor greebles. Teams were not told how many greebles total nor how many matched pairs were contained in each maze. We equated greeble density, size, distance between pairs, and the number of turns needed to navigate between the pairs in the mazes. We counterbalanced the order of presentation of the mazes such that within each condition half of the teams saw Mazes 1 and 2 in each of the two possible orders.

Before participants began to work through each maze, we showed them an overhead map of the maze for 60 seconds. The starting location was identified on this map only for the last 5 seconds to prevent teams from employing verbal strategies (such as memorizing turns). Teams were then given 3 minutes to navigate

² Mazes 3 and 4 had more complex pathways and 16 greebles each (versus 12 for Mazes 1 and 2), and performance scores decreased five fold, compared to Mazes 1 and 2. A floor effect thus obscured any systematic effects, and we were forced to discard the data.

the maze and tag as many greeble pairs as possible. Team members were not allowed to communicate while working on Maze 1, but were allowed to discuss the task freely for two minutes between Maze 1 and Maze 2, and to continue communicating while working on Maze 2.

Measures

We obtained two types of measures, assessing performance and collaboration.

Performance. We calculated each team's scores for each maze as the number of pairs of greebles tagged correctly, minus penalties for greebles tagged incorrectly (that is, ones that did not have a twin in the maze or whose twin was not tagged), plus a bonus if the team navigated enough of the territory to see every greeble in the maze. That score was the basis for participant earnings, which ranged from $-\$5.10$ to $\$6.80$ with a mean of $\$0.39$. Participants were guaranteed a minimum base payment of $\$20$ for completing the mazes, with any net positive earnings added to that base. Analyses reported here are based on the computed performance variable, not the amount paid.

Collaboration. Two raters independently viewed videotapes of each team and coded the amount of collaboration between members that occurred in the period from the end of Maze 1, when participants were first permitted to talk, until the end of Maze 2.³ Ratings were made separately on 3-point scales for navigation and for tagging, where 1 indicated "low or none," 2 indicated "moderate" collaboration, and 3 indicated "extensive" collaboration. Teams that exhibited moderate collaboration exchanged tips or pointers on how to keep track of where they were in the maze, and discussed how to recognize different greebles. Teams that exhibited extensive collaboration engaged in turn-by-turn coaching of the navigator by the tagger, and jointly decided whether or not a given greeble should be tagged.

One rater was the first author; the other was a laboratory research assistant. Ratings were made independently, and raters were blind to

experimental condition. Interrater reliability was .86 for collaboration on navigation and .70 for collaboration on object recognition. Ratings for each type of collaboration were averaged across raters and then summed to yield a total collaboration score that ranged from 2 to 6.

RESULTS

Because the performance of homogenous dyads whose members were both spatial visualizers or both object visualizers did not differ, subsequent analyses were conducted on all homogenous teams combined. All analyses were conducted using SPSS 12.0.1. for Windows™.

To understand the benefits of complementarity for teams, we conducted pair-wise comparisons of performance for congruent versus homogenous and congruent versus incongruent teams on total performance score for Mazes 1 and 2 together. Congruent teams performed better than homogeneous teams, $t(68) = 2.05$, $p = .04$, $d = 0.50$, demonstrating the benefits of having diverse task-specific abilities in a team. Furthermore, congruent teams performed better than incongruent teams, $t(58) = 1.96$, $p = .05$, $d = 0.51$, demonstrating the additional benefit of matching member abilities to roles.

To understand better the effects of collaboration, we analyzed the relationship between teams' level of collaboration and their performance on Maze 2 (because communication was not permitted while they worked through Maze 1, performance data on that maze were not included in this analysis). As shown in Table 1, incongruent teams collaborated significantly more than did both congruent, $t(58) = 3.69$, $p = .001$, $d = 0.97$, and homogenous teams, $t(62) = 2.50$, $p = .015$, $d = 0.64$. As is evident in Figure 2, collaboration was helpful for incongruent dyads, was associated with poorer performance for homogenous dyads, and had no effect for congruent dyads ($r = .48$, $p = .002$; $r = -.52$, $p = .001$; and $r = -.07$, $p = .72$, respectively). Furthermore, collaboration within incongruent dyads improved performance to a level where the performance of high collaboration/incongruent dyads (those with collaboration scores of 5 or higher) was not statistically different from congruent dyads, $t(37) \leq 1$, ns , $d = 0.21$. Comparison of the correlation coefficients relating collaboration and performance revealed significant differences for all pair-wise comparisons: incongruent dyads vs. congruent

³ A failure of the laboratory recording equipment caused the loss of sound data for six of the teams in the study, including 1 incongruent and 5 homogenous teams. As a result, collaboration could not be coded in these teams.

TABLE 1
Mean performance and collaboration scores by condition

Condition	N	Performance measure		
		Maze 1	Maze 2	Collaboration
Congruent	30			
<i>M</i>		0.57	1.50	3.50
<i>SD</i>		2.64	2.42	0.72
Incongruent	30			
<i>M</i>		-0.11	0.17	4.29
<i>SD</i>		1.62	2.30	0.92
Homogenous	40			
<i>M</i>		-0.21	0.38	3.70
<i>SD</i>		2.07	2.05	0.96

Note: Congruent teams performed better on Maze 2 than incongruent or homogenous teams, $p < .05$ in each case. Incongruent teams collaborated more than congruent or homogenous teams, $p < .05$ in each case. All other differences were nonsignificant.

dyads ($Z = 2.58$, $p = .009$); incongruent vs. homogenous dyads ($Z = 4.79$, $p = .0006$); and homogenous vs. congruent dyads ($Z = 2.31$, $p = .02$).

DISCUSSION

Previous studies have documented that individual differences in brain function underlie individual differences in performance, as we noted at the outset. In this study we provide initial evidence

that such individual differences affect not only performance of a single person, but performance when two people work together. What is not often discussed in cognitive neuroscience, let alone emphasized, is the fact that different brain systems must work together. Even within a single head, the two visual systems must work together. The present research suggests that it can be informative to regard teams in the same way, examining the ways in which the brain systems in different members' heads function together.

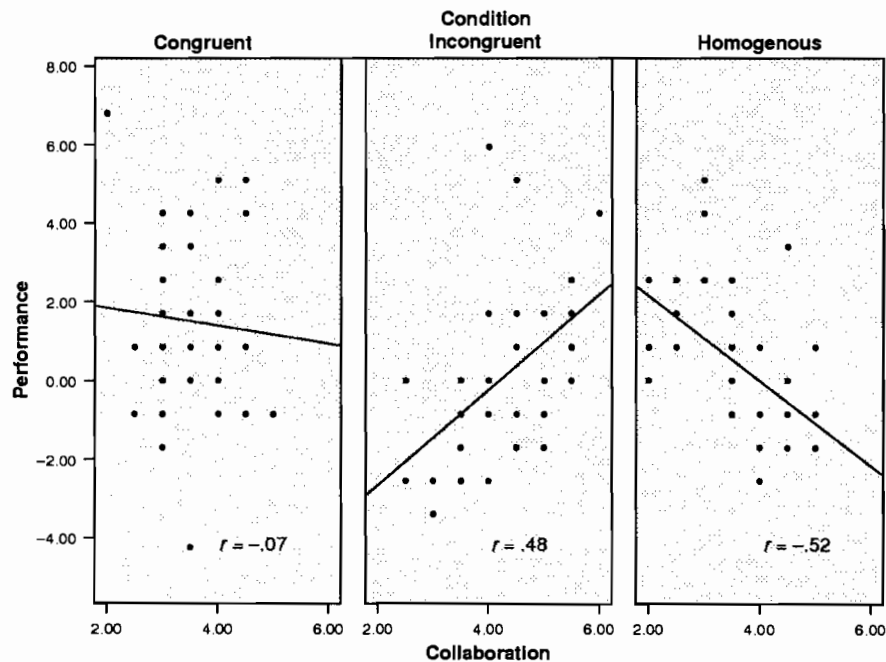


Figure 2. Least squares linear regression lines and correlation statistics demonstrating relationship between performance on Maze 2 and collaboration by condition.

Turning to the brain did in fact yield insight into how to compose effective teams. Consistent with prior research, having the right abilities *and* matching them to the appropriate role assignments are both critical to team effectiveness. In addition, the findings enrich understanding of the benefits of collaboration in teams. We found that when individuals with the requisite capabilities are assigned to the proper roles (the “congruent” condition), collaboration is not needed and, if it does occur, does not improve performance. When individuals are assigned roles that are inconsistent with their capabilities (the “incongruent” condition), however, members do spontaneously collaborate on their performance strategies. This occurs despite the fact that participants are not informed of either their own measured abilities or those of their partner. This stands in contrast to existing findings regarding the negative relationship between skill dissimilarity and helping behavior in work teams (Van der Vegt & Van de Vliert, 2005). In incongruent teams, all the requisite expertise is present for the task, but members have to figure out how to bring it to bear on their work. When they succeed in doing so, they can compensate for the initial misplacement of abilities.

Furthermore, in the “homogeneous” condition groups are missing one of the two capabilities required for task success. The more these groups collaborate, the *less* well they perform, because there is no way that collaboration can generate the missing expertise. The time members spend in fruitless discussion is directly at the expense of the time available for actual work on their task.

We have admittedly constrained the collaboration possibilities for the teams in our study by selecting a task involving two main skills and identifying individuals who either did or did not have those skills. However, we would argue that the findings generalize to other settings. Many tasks can be decomposed into skills that do not usually coexist in individual brains but are necessary for performance. This research suggests that paying attention to team composition with respect to those critical task-relevant skills, and the match between composition and performance strategy, is critical for team success.

The present findings not only speak to how effective teams should be composed, but also have implications for our understanding of the brain. Our results lead us to focus on the interactions among brain systems—both within and between individuals—and underline the

importance of considering the system as a whole, including the ways in which the different parts work together. Moreover, the results are compatible with a view of brain evolution that stresses the role of social interactions: Different brain systems may have evolved not only to work together within a single head, but also to work together between heads—that is, so that different systems are not only “plug compatible” within a single brain, but also across brains.

This example of research on the relationship between individual, brain-based capabilities and group interaction and performance suggests future directions for the evolving field of social neuroscience. To date, many “social” neuroscience studies have involved stimuli and tasks, such as facial photographs, word problems, and rating scales, that are related to social cognition but that are socially inert in themselves. A true “social neuroscience” must study the relationship between brain mechanisms and human interaction in social contexts. A prime example of this research is “hyperscanning” (Montague et al., 2002), in which two individuals play a game or otherwise interact while each one undergoes functional MRI to record neural activity.

The type of social neuroscience research reported here does not require linked MRI scanners. It can take advantage of the rich knowledge base developed in cognitive neuroscience regarding brain mechanisms of different mental abilities, as we have done in this study. Composing groups of interacting individuals according to their brain-based abilities, preferences, or behavioral tendencies (e.g., Krych-Appelbaum, Law, Barnacz, Johnson, & Keenan, 2006), provides a unique design for experiments that can demonstrate the effects of individual differences in neural mechanisms on patterns of group interaction.

In sum, our findings underscore the importance of considering neurologically-inspired variables in a wide range of human functions, including group interaction. Moreover, they underline the importance of coupling manipulations of team composition with measurements of performance strategy. Had we not examined team members’ interactions, we might have come to the erroneous conclusion that composition is the sole predictor of performance or that collaboration is universally helpful or harmful.

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